Study on the irradiation deformation of a pressure tube in CANDU 6 reactor using data from Wolsong units and crystal plasticity model

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1. Introduction

Irradiation deformation of a pressure tube is one of the most important issues in CANada Deuterium Uranium (CANDU) reactor because the pressure tube supports burning fuels and pressurized heavy water which cool the fuels. In terms of safety and efficiency, it is necessary to predict and manage the deformation. Irradiation and thermal creeps, and irradiation growth are known as active deformation mechanisms [1,2]. These deformation mechanisms can be a function of crystal properties, such as constitutive law and texture [3].

Accurately predicting the deformation requires not only an appropriate model, but also a proper analysis of the data used for prediction. In this study, physical model based on crystal plasticity theory was developed to describe the deformation behavior of the tube and the data analysis was performed on the data obtained from Wolsong units.

2. Modeling

Crystal plasticity model is basically governed by the following constitutive law for a single crystal:

$$\dot{\varepsilon}_{ij} = \dot{\gamma}_0 \sum_{\alpha} m_{ij}^{\alpha} \left(\frac{m_{kl}\sigma_{kl}}{\tau_0^{\alpha}} \right)^n \quad (1)$$

where $\dot{\varepsilon}_{ij}$ and σ_{kl} are a strain rate tensor in a single crystal and the applied stress on the give crystal, respectively. $\dot{\gamma}_0$ and n are the reference strain rate constant and the strain rate sensitivity exponent, respectively. m_{ij}^{α} is the Schmid tensor for α slip system which is expressed by $\frac{1}{2}\left(n_i^{\alpha} b_j^{\alpha} + n_j^{\alpha} b_i^{\alpha}\right)$, where n^{α} and b^{α} are the slip normal and direction vector of α slip system. τ_0^{α} is the critical resolved shear stress (CRSS) for a α slip system.

The above constitutive law is applied into commercial finite element method (FEM) software, ABAQUS 2017. With FEM framework, no consideration on the interactions between single crystals is necessary. Instead, the description of time integration procedure and the calculation of Jacobian matrix should be considered.

For the time integration procedure, the basic framework of kinematic relation should be taken account of. In the kinematic relation, the deformation gradient can be expressed by a multiplicative decomposition into elastic and plastic parts as:

$$\boldsymbol{F} = \boldsymbol{F}^e \boldsymbol{F}^p, where\ det\ \boldsymbol{F}^e > 0\ and\ \det \boldsymbol{F}^p = 1 \quad (2)$$

where $\boldsymbol{F}^e$ and $\boldsymbol{F}^p$ are deformation gradient tensor about the elastic deformation accounting the elastic stretching and the rigid-body rotation of crystal lattice and the incompressible plastic deformation due to dislocation slip, etc., respectively.

Since stress is a function of not the plastic deformation but the elastic one, the second Piola-Kirchoff stress ($\boldsymbol{S}$) can be described by the following simple linear form,

$$\boldsymbol{S} = \mathbb{C}^e : \boldsymbol{E}^e \quad (3)$$

where $\mathbb{C}^e$ and $\boldsymbol{E}^e$ are the forth order anisotropic elasticity tensor and the elastic Green-Lagrange strain tensor defined as $E^e = \frac{1}{2}(F^{eT}F^e - I)$, respectively.

For FE analysis, the stress should be computed through decomposing the elastic deformation tensor and the plastic one. The change of the plastic deformation tensor with a finite time increment can be derived by the following equation concerning the evolution of plastic deformation

$$\boldsymbol{L}^P = \dot{\boldsymbol{F}}^p \boldsymbol{F}^{p-1} = \sum_{\alpha} \dot{\gamma}^{\alpha} m^{\alpha} \quad (4)$$

The right term is identical with the basic constitutive equation (1). With the parameters dealt in the equation (1), the time integration procedure can be developed, then, the stress can be calculated [4].

3. Data from Wolsong units

Because measuring the amount of deformation of material during or after neutron irradiation requires considerable cost and time, there is not much data available for modeling and predicting the deformation. Therefore, it is necessary to understand the characteristics of the data more deeply.

Figure 1 (a) shows the cumulative number of measured channels as a function of year and figure 1 (b) displays the data excluding duplicated channels. For Wolsong unit 1, there were many measurements on various channels. On the other hand, for the other units, relatively less channels were selected but more measurements were carried out on the same channels than the unit 1.

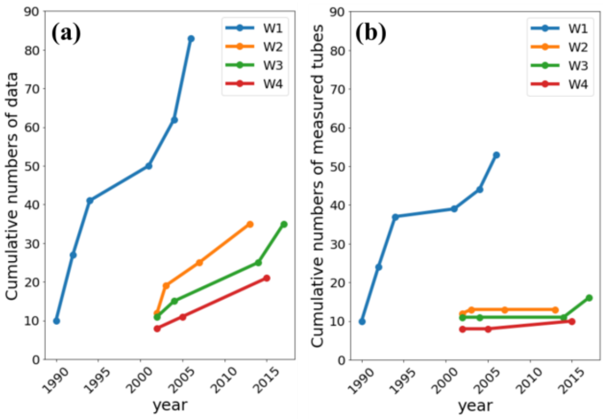

Figure 1. (a) the cumulative number of measured channels as a function of year and (b) the data excluding duplicated channels

With the measured data, the operating conditions have to be considered for the prediction as well. However, unlike the amount of deformation, the operation condition cannot be measured experimentally. Instead, the results obtained through theoretical calculations were used. Figure 2 shows the flux distributions of all pressure tubes, which are the same for all Wolsong units.

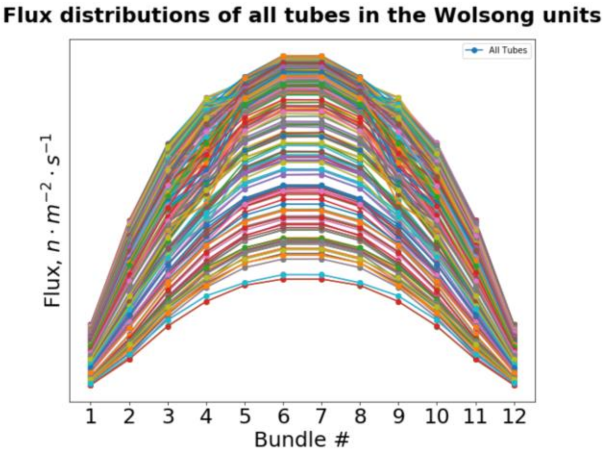

Figure 2. the flux distributions of all pressure tubes

4. Prediction

After going through the iterative process (figure 3) with an evolutionary strategy, which is an optimization technique based on ideas of evolution, the optimized model parameters were obtained. Then, pressure tube expansion strain rates were predicted using the parameters.

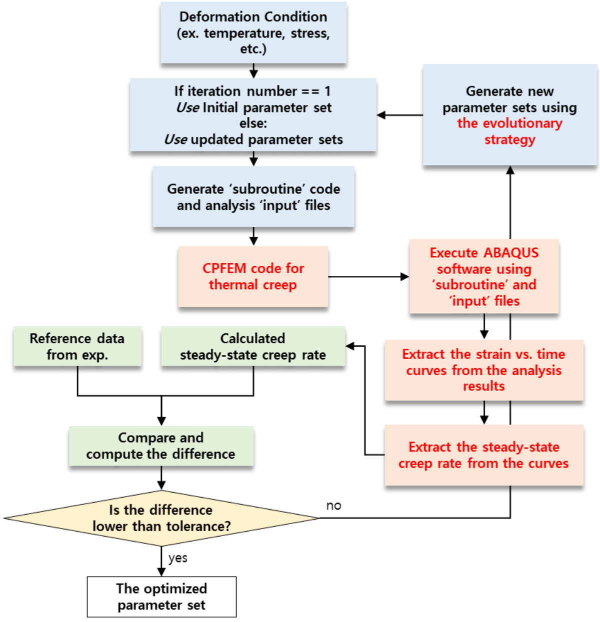

Figure 3. The schematic code flow used for optimizing parameters in FEM with crystal plasticity

Figure 4 shows some of the predicted results about channel F15 and K17 from Wolsong unit 4, and channel H13 and G05 from Wolsong unit 3. It can be seen that the predictive performance of the model is pretty good. One notable feature is that the discrepancy between measured and predicted values at bundle 12 location, where is coolant exit, is relatively high.

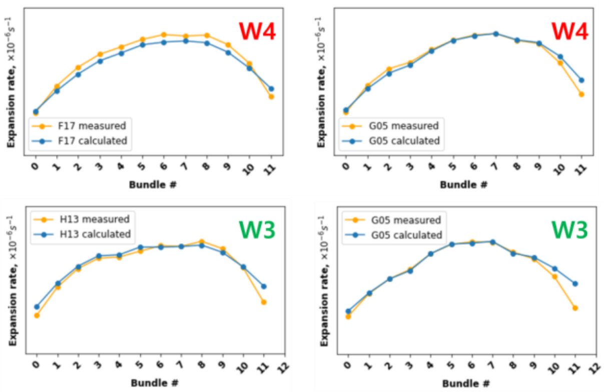

Figure 4. the comparisons of strain rates from the measured and calculated values about channel F15 and K17 from Wolsong unit 4 and channel H13 and G05 from Wolsong unit 3.

5. Conclusions

In the study, the irradiation deformation of pressure tube used in CANDU 6 reactor were modeled using crystal plasticity theory and FEM framework. Using the measured data from Wolsong units from 1 to 4 and the theoretically calculated operation conditions, we found the optimized parameters of the developed model through applying the in-house optimization codes. With the parameters, we predicted the strain rates about some selected tube channels and obtained pretty good match between the measured and calculated values. Therefore, we conclude that the developed model is a very useful method to predict and manage the irradiation deformation of the pressure tube.

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